

GROWTH RATES OF AMENABLE GROUPS

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ABSTRACT. Let F_m be a free group with m generators and let R be its normal subgroup such that F_m/R projects onto \mathbb{Z} . We give a lower bound for the growth rate of the group F_m/R' (where R' is the derived subgroup of R) in terms of the length $\rho = \rho(R)$ of the shortest nontrivial relation in R . It follows that the growth rate of F_m/R' approaches $2m - 1$ as ρ approaches infinity. This implies that the growth rate of an m -generated amenable group can be arbitrarily close to the maximum value $2m - 1$. This answers an open question by P. de la Harpe. In fact we prove that such groups can be found already in the class of abelian-by-nilpotent groups as well as in the class of finite extensions of metabelian groups.

1. INTRODUCTION

Let G be a finitely generated group and A a fixed finite set of generators for G . By $\ell(g)$ we denote the *word length* of an element $g \in G$ in the generators A , i.e. the length of a shortest word in the alphabet $A^{\pm 1}$ representing g . Let $B(n)$ denote the ball $\{g \in G \mid \ell(g) \leq n\}$ of radius n in G with respect to A . The *growth rate* of the pair (G, A) is the limit

$$\omega(G, A) = \lim_{n \rightarrow \infty} \sqrt[n]{|B(n)|}.$$

(Here $|X|$ denotes the number of elements of a finite set X .) This limit exists due to the submultiplicativity property of the function $|B(n)|$, see for example [5, VI.C, Proposition 56]. Clearly, $\omega(G, A) \geq 1$. A finitely generated group G is said to be of *exponential growth* if $\omega(G, A) > 1$ for some (which in fact implies for any) finite generating set A . Groups with $\omega(G, A) = 1$ are groups of *subexponential growth*.

Let $|A| = m$. It is known that $\omega(G, A) = 2m - 1$ if and only if G is freely generated by A [3, Section V]. In this case G is non-amenable whenever $m > 1$.

A finitely generated group which is nonamenable is necessarily of exponential growth [1]. The following interesting question is due to P. de la Harpe.

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Question. [5, VI.C 62] *For an integer $m \geq 2$, does there exist a constant $c_m > 1$, with $c_m < 2m - 1$, such that G is not amenable provided $\omega(G, A) \geq c_m$?*

We show that the answer to this question is negative. Thus, given $m \geq 2$, there exists an amenable group on m generators with the growth rate as close to $2m - 1$ as one likes.

It is worth noticing that for every $m \geq 2$ there exists a sequence of non-amenable groups (even containing non-abelian free subgroups) whose growth rates approach 1 (see [4]).

For a group H , we denote by H' its derived subgroup, that is, $[H, H]$.

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2. RESULTS

Let F_m be a free group of rank m with free basis A . Suppose that R is a normal subgroup of F_m . Assume that there is a homomorphism ϕ from F_m **onto** the (additive) infinite cyclic group such that R is contained in its kernel (that is, F_m/R has \mathbb{Z} as a homomorphic image). By a we denote a letter from $A^{\pm 1}$ such that

$$\phi(a) = \max\{\phi(x) \mid x \in A^{\pm 1}\}.$$

Clearly, $\phi(a) \geq 1$.

Throughout the paper, we fix a homomorphism ϕ from F_m **onto** \mathbb{Z} , the letter a described above and the value $C = \phi(a)$. By R we will usually denote a normal subgroup in F_m that is contained in the kernel of ϕ .

A word w over $A^{\pm 1}$ is called *good* whenever it satisfies the following conditions:

- (1) w is freely irreducible,
- (2) the first letter of w is a ,
- (3) the last letter of w is not a^{-1} ,
- (4) $\phi(w) > 0$.

Let D_k be the set of all good words of length k and let d_k be the number of them.

Lemma 1. *The number of good words of length $k \geq 4$ satisfies the following inequality:*

$$(1) \quad d_k \geq 4m(m-1)^2(2m-1)^{k-4}.$$

In particular, $\lim_{k \rightarrow \infty} d_k^{1/k} = 2m - 1$.

Proof. Let Ω be the set of all freely irreducible words v of length $k - 1$ satisfying $\phi(v) \geq 0$. The number of all freely irreducible words of length $k - 1$ equals $2m(2m - 1)^{k-2}$. At least half of them has a nonnegative image under ϕ . So $|\Omega| \geq m(2m - 1)^{k-2}$.

Let Ω_1 be the subset of Ω that consists of all words whose initial letter is different from a^{-1} . We show that $|\Omega_1| \geq ((2m - 2)/(2m - 1))|\Omega|$. It is sufficient to prove that $|\Omega_1 \cap A^{\pm 1}u| \geq ((2m - 2)/(2m - 1))|\Omega \cap A^{\pm 1}u|$ for any word u of length $k - 2$. Suppose that $a^{-1}u$ belongs to Ω . For every letter b one has $\phi(b) \geq \phi(a^{-1})$. Therefore, $bu \in \Omega_1$ for every letter $b \neq a^{-1}$ provided bu is irreducible. There are exactly $2m - 2$ ways to choose a letter b with the above properties. Hence $|\Omega_1 \cap A^{\pm 1}u|$ and $|\Omega \cap A^{\pm 1}u|$ have $2m - 2$ and $2m - 1$ elements, respectively. If $a^{-1}u \notin \Omega$, then both sets coincide.

Now let Ω_2 denote the subset of Ω_1 that consists of all words whose terminal letter is different from a^{-1} . Analogous argument implies that $|\Omega_2| \geq ((2m - 2)/(2m - 1))|\Omega_1|$. It is obvious that av is good provided $v \in \Omega_2$. Therefore, the number of good words is at least

$$|\Omega_2| \geq \frac{2m - 2}{2m - 1}|\Omega_1| \geq \left(\frac{2m - 2}{2m - 1}\right)^2 |\Omega| \geq 4m(m - 1)^2(2m - 1)^{k-4}.$$

□

To every word w in $A^{\pm 1}$ one can uniquely assign the path $p(w)$ in the Cayley graph $\mathcal{C} = \mathcal{C}(F/R, A)$ of the group F/R with A the generating set. This is the path that has label w and starts at the identity. We say that a path p is *self-avoiding* if it never visits the same vertex more than once.

Let $\rho = \rho(R)$ be the length of the shortest nontrivial element in a normal subgroup $R \leq F_m$.

Lemma 2. *Let R be a normal subgroup in F_m that is contained in the kernel of a homomorphism ϕ from F_m onto \mathbb{Z} . Suppose that $k \geq 2$ is chosen in such a way that the following inequality holds:*

$$(2) \quad \rho(R) > Ck(2k - 3) + 2k - 2.$$

Then any path in the Cayley graph \mathcal{C} of F_m/R labelled by a word of the form $g_1g_2 \cdots g_t$, where $t \geq 1$, $g_s \in D_k$ for all $1 \leq s \leq t$, is self-avoiding.

Proof. If p is not self-avoiding, then let us consider its minimal subpath q between two equal vertices. Clearly, $|q| \geq \rho \geq k$. Therefore, q can be represented as $q = g'g_i \cdots g_jg''$, where g_i, \dots, g_j are in D_k , the word g' is a proper suffix of some word in D_k , the word g'' is a proper prefix of some word in D_k . We have $|g'|, |g''| \leq k - 1$ so $|g_i \cdots g_j| > Ck(2k - 3)$. This implies that $j - i + 1$ (the number of

sections that are completely contained in q) is at least $C(2k - 3) + 1$. Obviously, $\phi(g') \geq -C(k - 1)$ and $\phi(g'') \geq -C(k - 2)$ (we recall that g'' starts with a if it is nonempty). On the other hand, $\phi(g_s) \geq 1$ for all s . Hence $\phi(g_i \cdots g_j) \geq j - i + 1 \geq C(2k - 3) + 1$ and so $\phi(g'g_i \cdots g_jg'') \geq 1$, which is obviously impossible because for every $r \in R$ one has $\phi(r) = 0$. \square

Theorem 1. *Suppose that R is a normal subgroup in the free group F_m that is contained in the kernel of a homomorphism ϕ from F_m onto \mathbb{Z} . Let C be the maximum value of ϕ on the generators or their inverses. Let $\rho = \rho(R)$ be the length of the shortest cyclically irreducible nonempty word in R . If a number $k \geq 4$ satisfies the inequality*

$$(3) \quad \rho \geq Ck(2k - 3) + 2k - 1,$$

then the growth rate of the group F_m/R' w.r.t. the natural generators is at least

$$(2m - 1) \cdot \left(\frac{4m(m - 1)^2}{(2m - 1)^4} \right)^{1/k}.$$

Proof. We use the following known fact [2, Lemma 1]. A word w belongs to R' if and only if, for any edge e , the path labelled by w in the Cayley graph of the group F_m/R has the same number of occurrences of e and e^{-1} . Hence, if we have a number of different self-avoiding paths of length n in the Cayley graph of F_m/R , then they represent different elements of the group F_m/R' . Moreover, all the corresponding paths in the Cayley graph of F_m/R' are geodesic so these elements have length n in the group F_m/R' .

Suppose that the conditions of the theorem hold. For every n , one can consider the set of all words of the form $g_1g_2 \cdots g_n$, where all the g_i 's belong to D_k . By Lemma 2 all these elements give us different self-avoiding paths in the Cayley graph of F_m/R . Hence for any n we have at least d_k^n different elements in the group F_m/R' that have length kn . Therefore, the growth rate of F_m/R' is at least $d_k^{1/k}$. It remains to apply Lemma 1. \square

One can summarize the statement of Theorem 1 as follows: if all relations of F_m/R are long enough, then the growth rate of the group F_m/R' is big enough. Notice that we cannot avoid the assumption that F_m/R projects onto \mathbb{Z} . Indeed, for any number ρ , there exists a finite index normal subgroup in F_m such that all the nontrivial elements in this subgroup are longer than ρ . If R was such a subgroup, then F/R' would be a finite extension of an abelian group and its growth rate would be equal to 1.

Theorem 2. *Let F_m be a free group of rank m with free basis A and let ϕ be a homomorphism from F_m onto \mathbb{Z} . Suppose that*

$$\ker \phi \geq R_1 \geq R_2 \geq \cdots \geq R_n \geq \cdots$$

is a sequence of normal subgroups in F_m . If the intersection of all the R_n 's is trivial, then the growth rates of the groups F_m/R'_n approach $2m - 1$ as n approaches infinity, that is,

$$\lim_{n \rightarrow \infty} \omega(F_m/R'_n, A) = 2m - 1.$$

Proof. Since the subgroups R_n have trivial intersection, the lengths of their shortest nontrivial relations approach infinity, that is, $\rho(R_n) \rightarrow \infty$ as $n \rightarrow \infty$. Let $k(n) = \left\lceil \sqrt{\rho(R_n)/2C} \right\rceil$, where C is defined in terms of ϕ as above). Obviously, inequality (3) holds and $k(n) \rightarrow \infty$. Now Theorem 1 implies that the growth rates of the groups F_m/R'_n approach $2m - 1$. \square

Now we show that for every m there exists an amenable group with m generators whose growth rate is arbitrarily close to $2m - 1$.

Theorem 3. *For every $m \geq 1$ and for every $\varepsilon > 0$, there exists an m -generated amenable group G , which is an extension of an abelian group by a nilpotent group such that the growth rate of G is at least $2m - 1 - \varepsilon$.*

Proof. It suffices to take the lower central series in the statement of Theorem 2 (that is, $R_1 = F'_m$, $R_{i+1} = [R_i, F_m]$ for all $i \geq 1$). The subgroups R_n ($n \geq 1$) have trivial intersection and they are contained in F'_m . So all of them are contained in the kernel of a homomorphism ϕ from F_m onto \mathbb{Z} (one of the free generators of F_m is sent to 1, the others are sent to 0). The groups $G_n = F_m/R'_n$ are extensions of (free) abelian groups R_n/R'_n by (free) nilpotent groups F_m/R_n so all the groups G_n are amenable. The growth rates of them approach $2m - 1$. \square

Notice that one can take the sequence $R_n = F_m^{(n)}$ of the n th derived subgroups as well (that is, $R_1 = F'_m$, $R_{i+1} = R'_i$ for all $i \geq 1$). It is not hard to show that $\rho(R_n)$ grows exponentially. The groups $F_m/R'_n = F_m/R_{n+1}$ are free soluble. Their growth rates approach $2m - 1$ very quickly. For instance, the growth rate of the free soluble group of degree 15 with 2 generators is greater than 2.999.

One more application of Theorem 3 can be obtained as follows. The set of finite index subgroups of F_m is countable so one can enumerate them as $N_1, N_2, \dots, N_i, \dots$. Let $M_i = N_1 \cap N_2 \cap \cdots \cap N_i$ and let $R_i = M'_i$ for all $i \geq 1$. Obviously, the subgroups M_i (and thus R_i)

have trivial intersection. Indeed, F_m is residually finite and so the subgroups N_i intersect trivially. As above, all the R_i 's are contained in F'_m so they are contained in the kernel of a homomorphism ϕ from F_m onto \mathbb{Z} . Hence the growth rates of the groups $F_m/R'_i = F_m/M''_i$ approach $2m - 1$. These groups are extensions of M_i/M''_i by F_m/M_i , that is, they are finite extensions of (free) metabelian groups.

Therefore, in each of the two classes of groups: 1) extensions of abelian groups by nilpotent groups, 2) finite extensions of metabelian groups, there exist m -generated groups with growth rates approaching $2m - 1$.

Remark. A. Yu. Ol'shanskii suggested the following improvement. Let p be a prime. Since F_m is residually a finite p -group, one can get a chain $M_1 \geq M_2 \geq \dots$ of normal subgroups with trivial intersection, where F_m/M_i are finite p -groups. Now let $R_i = \ker \phi \cap M_i$. The group F_m/R_i is a subdirect product of \mathbb{Z} and a finite p -group. In particular, it is nilpotent. Besides, it is an extension of \mathbb{Z} by a finite p -group and an extension of a finite p -group by \mathbb{Z} , as well. So F_m/R'_i will be abelian-by-nilpotent and metabelian-by-finite at the same time. (In fact, the metabelian part is an extension of an abelian group by \mathbb{Z} .) Also one can view F_m/R'_i as an extension of a virtually abelian group by \mathbb{Z} .

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